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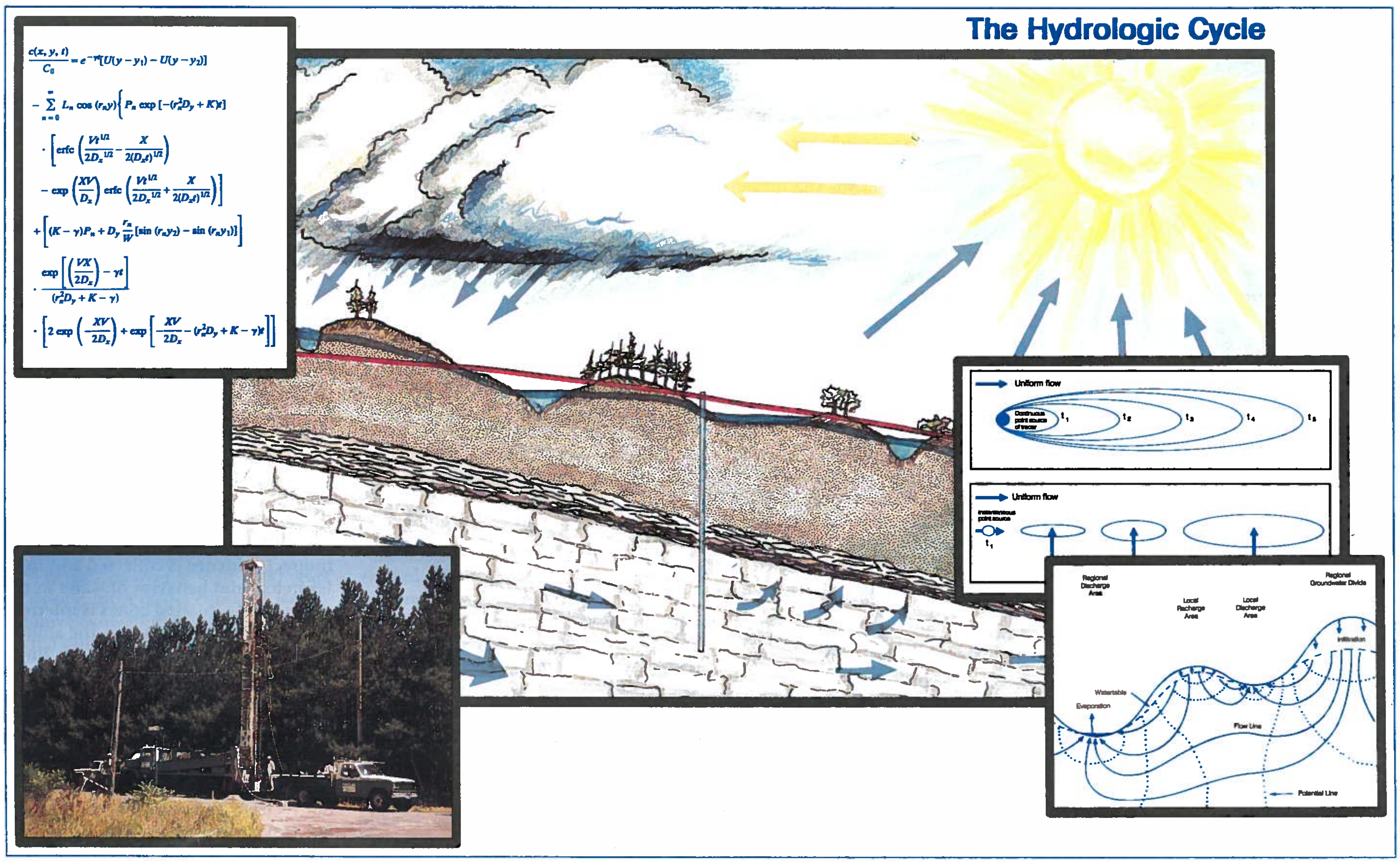
INSIDE



Hydrogeology: It Is

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ABSTRACT

The geoscience discipline of hydrogeology is experiencing vigorous growth and visibility, but also an unresolved tolerance within the geoscience community. The study of fluids within geologic materials and water as a geologic agent is as fundamental to geology as is study of mineralogy and petrology. Moreover, hydrogeology is also highly interdisciplinary, having interplay with other scientific, institutional, and engineering disciplines. Significant increased research is anticipated in both small-scale and regional-scale problem areas—all oriented to the behavior of fluids in geologic environments. Perhaps the single most pressing concern in hydrogeologic circles is the imbalance between supply and demand—the paucity of bona fide hydrogeology candidates for employment at virtually all levels. Those employers facing staff shortages are turning to persons who have little or no actual hydrogeological education or training.

INTRODUCTION

The discipline of hydrogeology has been declaimed, criticized, and sometimes dismissed within the geoscience community as too useful, too applied. Maybe this is so, in classical terms. But the fact remains: Hydrogeology is an interdisciplinary science within the geosciences. Concepts and terminology from nongeoscience disciplines incorporated into hydrogeology are perhaps more numerous than for the other geosciences. However, as Alvarez (1991) has noted, "There seems to be a close association between interdisciplinary science and revolutionary developments in geology...." The purpose of this article is to present the role of hydrogeology within the geosciences and to discuss the phenomenal growth in hydrogeology, current and future directions for the science, and several issues relating to supply and demand.

Hydrogeology is currently the fastest growing discipline within the geosciences. This growth is not a coincidence. It is a reflection of public, governmental, and industrial awareness of the value and fragility of water resources and the response of the geoscience community to that awareness. Few could quarrel with the highly visible employment of hydrogeologists in recent years. Claudy (1991a) has pointed out that the consulting industry will continue to be the fastest growing employment sector for geoscientists over the next several years; within that sector, hydrogeologists are in the greatest demand. Claudy (1991b) also noted that "related professional scientists" are increasingly in high demand.

In tandem with the market demand for hydrogeologists has been an ever-increasing impetus for research in hydrogeology. Over the past 10 years, research has been explosive because of the recognition of widespread groundwater contamination (see, for example, Moore and Rosenshein, 1990; Rosenshein et al., 1991). Thus, considerable research in the past decade has been concerned with processes that control groundwater flow and mass transport of chemicals in ground-water flow systems.

In spite of the employment demands for hydrogeologists and society's needs for hydrogeology, what is surprising is the volume of argument in geoscience circles as to the probable longevity of this discipline. In the past and to some extent continuing today, many in the academic community have argued about the appropriateness of hydrogeology being taught in a geoscience department (vs. an engineering department). Most geologists historically have been the interpreters of Earth history—a view that remains entrenched today. Geology periodically has seen a succession of applied areas, including ore deposits, petroleum geology, hydrogeology, and "global change." The experience for the traditional geologist includes envy (usually short term) to see so many dollars for research and possibilities for student employment pass them by, disappointment to see many opportunities for outstanding basic research lost in the stampede to solve industrial problems, and vast retrenchments in schools and programs once the bubble bursts (as

Hydrogeology *continued on p. 94*

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Hydrogeology *continued from p. 93*

it has in ore deposits and petroleum). Will it be any different with hydrogeology? If hydrogeology's fate is the same as that of ore deposits and petroleum, then the traditionalists' view of these applied fields will have been correct.

Time will tell. However, popularity and current trends aside, hydrogeology is a quantitative science with a significant and purposeful development from theory to practice. At the heart of hydrogeology is the need to understand the geologic framework through which fluids move as the critical control for interpreting water quality or quantity. Consider this statement about geologic aspects of water resource issues: "Few geologists find themselves able to pursue the subject of [ground water] into its practical details because of the multitude of more obtrusive issues pressed upon their attention." Modern-day statement? Not so. Those words were written by T. C. Chamberlin in 1884, just before he assumed the presidency of the Wisconsin Academy of Sciences, Arts, and Letters (Stephenson, 1978). One could argue that not much has changed in the past 100 years.

Hydrogeology Defined

There is considerable confusion about differences between such terms as "geohydrology" and "hydrogeology." Many recent authors support a concept that geohydrologists are more engineering oriented in that they deal with aquifer mechanics. Hydrogeologists deal with a broader array of topics, including, but not limited to, ground-water flow-system analysis. Domenico and Schwartz (1990) took an interesting approach to defining hydrogeology: they delayed a definition until they first developed an understanding of what hydrogeology is today and how it got that way, and who were some of the significant contributors to the field. Because we do not have the space to follow their lead to the fullest, we will skip ahead and offer a definition of hydrogeology: the interdisciplinary science of the study of water and its interrelation with rocks, soil, and humans, with an emphasis on ground water. We supplement this definition with discussions from several other sources:

Domenico and Schwartz, 1990: "... the study of the laws governing the movement of subterranean water, the mechanical, chemical, and thermal interaction of this water with the porous solid, and the transport of energy and chemical constituents by the flow."

Fetter, 1988: "... the interrelationship of geologic materials and processes with water."

Meyer et al., 1988: "... an interdisciplinary science that is dependent upon many branches of the physical, chemical, and biological sciences. It is an offspring of geology and hydrology...."

AGI *Glossary of Geology* (Bates and Jackson), 1987: "The science that deals with subsurface waters and with related geologic aspects of surface waters."

Narasimhan, 1982: "... the discipline concerned with those geologic processes that are influenced by water."

Two recent hydrogeological publications offer no succinct definition of hydrogeology but stress concepts of occurrence and movement of ground water as a resource: Freeze and Cherry (1979) and Back et al. (1988). These references are both substantial contributions directed toward hydrogeologists or those who aspire to become hydrogeologists.

The common thread in all the definitions above is that hydrogeology requires an understanding of geology.

HYDROGEOLOGY TODAY

Hydrogeologists work for federal and state research groups, agencies, or surveys, for hundreds of private environmental and engineering consulting companies, in environmental groups for major industries and special interest groups, and as teachers and researchers in colleges, universities, and national laboratories. The actual number of scientists working in the field of hydrogeology is difficult to ascertain for two reasons: (1) all hydrogeologists do not belong to a single professional organization and (2) because of the interdisciplinary nature of hydrogeology, it is difficult to separate the traditional geologically trained professionals from those associated with other related disciplines. We surveyed the membership of four professional organizations serving hydrogeologists and obtained employment statistics in an attempt to approximate the number of hydrogeologists (Table 1). The Association of Ground Water Scientists and Engineers (AGWSE), the largest organization that specifically seeks members who study ground water, states that between 15,000 and 20,000 professionals are currently working in hydrogeology or related fields.

TABLE 1. Membership in Organizations Specializing in Hydrology and Hydrogeology, 1989–1990

Organization	Membership
Association of Ground Water Scientists and Engineers	16,300
American Geophysical Union, Hydrology Division	4748
American Water Resources Association	2934
Geological Society of America, Hydrogeology Division	1871
U.S. Government Hydrologist Rating (1987 data)	2298
American Institute of Hydrology	1000

Of the more than 15,000 members of GSA, 1871 are in the Hydrogeology Division, which is the second largest of GSA's divisions (Table 2).

TABLE 2. Membership of the Largest Six Divisions of GSA, 1990

Division	Membership
Structural	2140
Hydrogeology	1871
Quaternary	1437
Engineering	1175
Sedimentary	1043
Geophysics	590

Note: Data from T. M. Moreland, GSA Membership Services (February 1991, personal commun.)

In the hydrogeological community two major kinds of hydrogeologists can be broadly identified: practicing and research-oriented. The research group includes those professionals who are exploring the role of ground water as a geologic agent. They are looking at such issues as single- and multi-component flow and the interrelated processes of mass and energy transport. There is exciting work to establish the relation between ground water and many of the classical problems of geology, including petroleum migration, ore genesis, and contaminant plume behavior in rocks or soils with low hydraulic conductivity and, frequently, secondary porosity. Many studies are concerned with a mathematical description of flow and transport phenomena.

The practitioners are applying a rapidly increasing technology and scientific understanding to contemporary problems. The dominant problems of the day concern water quality, closely followed by water supply. Current highly visible efforts are being made in: contaminant hydrogeology; conflicts and competition for supply between agriculture, municipalities, industry, and recreation; aquifer mechanics and ground-water–surface-water interaction; and consequences of mining ground water (e.g., land-surface subsidence and salt-water encroachment).

One recent activity bears mention. Hydrogeologists need either to be versed in geochemistry or to team with geochemists and other professionals to characterize the hydrogeologic system (including the mechanics and chemistry of the transport of solutes and contaminants in earth material) and to describe and quantify methods to represent saturated and unsaturated water flow (see, for example, Krabbenhoft et al., 1990a, 1990b). The focus in hydrogeology has shifted from ground-water flow analysis to chemical transport (Konikow and Papadopulos, 1988).

The Practice of Hydrogeology

Hydrogeologists attempt to characterize the occurrence, movement, quantity, and quality of water below the land surface. This task is mainly one of inference and interpretation: indirect evidence is collected and interpreted, and behavior of water in the vadose and saturated zones is inferred. Over the past several years, the ability to characterize these systems has improved dramatically, and the need to predict flow and contaminant migration has increased.

Today, hydrogeologists can describe and quantify regional groundwater systems. However, as we narrow our focus to parts or subsystems of larger systems, the geologic framework becomes more complex, demanding additional analysis. Because hydrogeologists do not always have the advantage of detailed three-dimensional views of these systems, they rely on geologic training and principals of physics, mathematics, and chemistry to diagnose the system and predict cause-and-effect relations. Hydrogeologic studies more frequently should include the team work of one or more specialists including mathematicians, statisticians, geochemists who work with inorganic and organic material, scientists who study soils and vadose-zone flow and transport, and microbiologists, in addition to the hydrogeologist.

An interesting aspect of hydrogeology is its close involvement with institutional issues. Representatives of both the practicing and research-oriented groups sit on advisory panels—at state, province, and national levels—to contribute to resolution of legal, economic, and institutional issues.

Today's practicing hydrogeologist is deeply involved with analysis, site characterization, and remediation of ground-water contamination resulting from spills of volatile organic chemical constituents and petroleum hydrocarbons. Contaminant-transport modeling has joined ground-water flow modeling as an essential tool in the kit required by hydrogeologists. Hydrogeologists are increasingly caught between major advances in the science and pressures from regulatory agencies to provide answers (Schwartz et al., 1990).

Research hydrogeologists are focusing on unraveling the behavior of fluids in porous media and are delving into such issues as the evaluation of mass-transport processes, modeling techniques for complex flow and transport problems, and field studies related to contaminants. Current efforts are reflected in published research; Table 3 presents a summary of journal articles published in the past two years, categorized by subject matter.

TABLE 3. Ground-Water Articles Published in Six Leading Journals, 1988–1990

Ground-water subject	Number
Solute transport, geochemistry	191
Ground-water and soil-water flow	150
Field techniques	76
Parameter identification	47
Recharge and evapotranspiration	29
Management	28
Surface water–ground-water interaction	16
Coastal ground-water systems	13
Karst systems	7

Note: Journals include *Water Resources Research, Journal of Hydrology, Ground Water Monitoring Review, American Water Resources Bulletin,* and *Geological Society of America Bulletin.*

PERSPECTIVES ON THE PAST

Domenico and Schwartz (1990, p. 5) presented an interesting statistic: over 95% of all the hydrogeologists who ever lived are still alive and still working. The important message in this is that hydrogeology is a relatively new science within the broad realm of geoscience. Although the concepts and tools used by hydrogeologists have been generated over at least 6000 years of history, most of the concepts we utilize have evolved out of research conducted during the past 50 to 60 years.

There is a plethora of articles that summarize the historical elements of and recent advances in hydrogeology—for example: Bredehoeft (1976), Anderson (1979), Maxey (1979), Bredehoeft et al. (1982), Narasimhan (1982), Back and Freeze (1983), Freeze and Back (1983), Back et al. (1988), Fetter (1988), Domenico and Schwartz (1990).

The concept of the hydrologic cycle is central to any discourse on historical perspectives. Simply stated, the hydrologic cycle is a dynamic interaction between the sun's energy and Earth's gravity. Water is the medium of concern in this interaction between opposing forces. Although the hydrologic cycle is simple and the hydrologic character is reduced to three elements—climate, geology, and topography—centuries passed before the quantitative development of the science. Water-supply wells are known from at least 6000 years ago, but until the 1600s, scientific fact resolving hydrologic concerns was not forthcoming. There were many myths, some of which persist today. Back (1981) discussed water resources and water-related mythology and their role in water-resources management and even in success of civilizations.

In the 17th century, definition of the hydrologic cycle evolved. A series of 19th century investigators or events developed concepts and support for what is now within the realm of hydrogeology. These included Darcy's law, Dupuit's equilibrium equation, A. Thiem's use of tracers, and T. C. Chamberlin's work on artesian-water systems.

The 20th century has been characterized by quantification of ground-water flow and eventually chemical and heat transport. This century can be divided into three periods of differing activity.

1900–1935. Significant contributions were made by Slichter, G. Thiem, Terzaghi, and others. In 1923, O. E. Meinzer made a very important contribution with publication of two papers on the occurrence of ground water in the United States, and an outline of ground-water hydrology. These papers were among the first state-of-the-art contributions to the discipline of hydrogeology (see Meinzer, 1923a, 1923b).

1935–1960. A major contribution by C. V. Theis in 1935 was his development of the nonequilibrium flow equation. Using the Theis approach, the transient conditions of ground-water flow around pumping wells could be described. The transient flow of ground water and well hydraulics in general were the focus of attention by such researchers as Jacob and Hantush and their students. M. King Hubbert presented a monumental paper on ground-water motion (Hubbert, 1940). Hubbert's work was among the first to discuss natural flow of ground water in large basins. Thus, between 1935 and 1940, aquifer mechanics and ground-water flow-system analysis were introduced; they still govern hydrogeological research today.

Another notable contribution, much evident by the 1950s, was the evolution of chemical hydrogeology. Researchers of this era contributing to what is now called hydrogeochemistry included Stiff, Hem, Chebotarev, Back, and Garrels.

The 1930s dust-bowl days and World War II created situations where, for the first time in North America, considerable emphasis was placed on ground water as a major supply. This demand was partly due to the need for large supplies of constant-temperature water and partly due to development in well-drilling and well-construction techniques.

1960–1991. The changes in hydrogeology have been dramatic over the past 30 years. Both physical and chemical hydrogeology subdisciplines have received exponentially increasing research contributions. Ground-water flow-system analysis was related to topographic controls by Toth (1962, 1963) and subsequently to geologic controls by Freeze and Witherspoon (1966; Freeze, 1967). Subsequent researchers have added to basin-wide flow analysis, including deep-basin analysis.

This era is also characterized by dedicated efforts on the part of a handful of educators to begin training students who today are responsible for teaching or research in hydrogeology.

Hydrogeochemical analyses have been driven in part by significant institutional factors. The 1970s and 1980s were decades in which major federal environmental laws were enacted that led to creation of "contaminant hydrogeology." These laws included: the Clean Water Act; the Safe Drinking Water Act; the Surface Mining Act; the Resource Conservation and Recovery Act (RCRA); the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); and others more recently that add, or will add, leaking storage tanks, mining wastes, and radioactive wastes to the list of concerns.

FUTURE DIRECTIONS

Much of the recent growth in hydrogeology has been related to the regulatory drive for environmental protection and cleanup. The passage and implementation of the Resource Conservation and Recovery Act (RCRA) in 1976, with its requirement for ground-water monitoring, and the advent of the Superfund program to clean up

Hydrogeology *continued on p. 99*

Committee Service Provides Way to Affect GSA

The GSA Committee on Committees wants your help. As one of his duties, Vice-President E-an Zen has appointed a group to look for talent to serve GSA as members of our committees and as our representatives to other organizations.

The Committee on Committees will meet in late August or early September and will present at least two nominations for each open position to the Council at its October 23 meeting in San Diego, California. During the meeting, individual councilors may add other names to the lists for consideration. The entire Council will then select appointees for all positions, thus completing the process of bringing new expertise into Society affairs.

The Committee on Committees for 1991 consists of the following people: Chairman Robert D. Hatcher, Jr., Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996-1410, (615) 974-6565; Richard L. Armstrong, Department of Geological Sciences, University of British Columbia, Vancouver, B.C. V6T 2B4, Canada, (604) 228-6208; Sharon Mosher, Department of Geological Sciences, University of Texas, Austin, TX 78713, (512) 471-4135; A.R. (Pete) Palmer, Geological Society of America, P.O. Box 9140, Boulder, CO 80301, (303) 447-2020; H. Catherine W. Skinner, P.O. Box 894, Woodbury, CT 06798, (203) 432-3787; David B. Stewart, U.S. Geological Survey, 959 National Center, Reston, VA 22092, (703) 648-6945.

This group is broadly based, both geographically and in disciplines, but its members cannot possibly know all the GSA members who are potential candidates for serving the Society. You can help them by volunteering yourself or by suggesting names of others you think should be considered for any of the openings and submitting your nomination on the form on page 98.

In making recommendations, please give serious consideration to the special qualifications of the individual for a particular committee. To assist you in nominating GSA members for these various positions, see the following brief summaries of what each committee does and what qualifications are desirable. *Please be sure that your candidates are Members or Fellows of the Society and that they meet fully the requested qualifications.*

All nominations received at headquarters on the official one-page form will be forwarded to the committee members. **DEADLINE: JULY 15, 1991**. Information requested on this form will assist the Committee on Committees with their recommendations for the 1992 committee vacancies. Council has determined that *"unless the nomination form is complete in every respect, the nomination will not be considered. Complete backup material must be supplied by the volunteer or the nominator."* Please use one form per candidate. (Additional forms may be copied or requested from GSA headquarters.)

Listed below are the committees and the number of vacancies that will occur. Appointments will be made by the GSA Council at its meeting in San Diego in October.

Committees and Qualifications

Day Medal **(2 vacancies)**
Selects candidates for the Arthur L. Day Medal.

Committee members should have knowledge of those who have made "distinct contributions to geologic knowledge through the application of physics and chemistry to the solution of geologic problems."

Education **(1 vacancy)**
Stimulates interest in the importance and acquisition of basic knowledge in the earth sciences at all levels of education.

Committee members work with other interested scientific organizations and science teachers' groups to develop precollege earth-science education objectives and initiatives. The committee also promotes the importance of earth science education to the general public.

Geology & Public Policy **(3 vacancies)**
Translates knowledge of the earth sciences into forms most useful for public discussion and decision making.

Committee members should have an awareness of public policy and decisions involving the science of geology. They should also be able to develop, disseminate, and translate information from the geological sciences into useful forms for the general public and for the Society membership; they should be familiar with appropriate techniques for the dissemination of information.

Honorary Fellows **(2 vacancies)**
Selects candidates for Honorary Fellows, usually non–North Americans.

Committee members should have knowledge of geologists throughout the world who have distinguished themselves through their contributions to the science.

Long-Range Planning **(1 vacancy)**
Assesses the purpose and objectives of the Society in each of its major program areas, and reviews proposals for new policies or program initiatives. Reviews annually the basic mission, the strategic objectives, and goals of the Society with respect to changes in the science of geology.

Committee *continued on p. 98*

Attention Journal Subscribers

The March and April issues of *GSA Bulletin* and *Geology* were mailed to U.S. and Canadian addresses without packaging in an attempt to reduce our use of poly. The experiment has failed. Damage claims were unexpectedly high, and many subscribers wrote or called to ask us to return to the protective packaging.

Our primary goal is to deliver your journals in first-class condition. It is now clear that packaging is required, and we believe that functional, recyclable poly packaging is better than any other packaging medium available to us—and we have tried them all.

With the May issues, we are returning to poly packaging. If you subscribe to both journals, your May issues may or may not be combined in one package, but your June issues will be. Our thanks to all who wrote or called to keep us informed and share your feelings. *—Jim Clark, Publications Production Manager*

Hydrogeology *continued from p. 95*

hazardous-waste sites clearly provided a major growth opportunity for hydrogeology. Remediation and cleanup issues in North America, Europe, and elsewhere will be addressed for the next 50 or more years. As a result, a variety of research efforts will evolve, focusing on the behavior of fluids in all geologic environments and particularly relating to transport of chemicals (i.e., definition of contaminant plume in terms of position and movement). An issue confronting hydrogeological practioners and researchers alike is the ability to restore contaminated aquifer systems to required cleanup levels. Travis and Doty (1990) found that, on the basis of the past 10 years of rather unsuccessful remediation efforts, hydrogeologists may be required to concentrate on plume containment rather than on aquifer system restoration.

Although unit-specific studies will be demanding, interest in regional-scale issues will be renewed. Moreover, the interrelation among areas of classical concern—petroleum, ore deposits, diagenesis, tectonics, sedimentology, and hydrogeology—will expand. Toth (1988), for example, concluded that "factual knowledge concerning petroleum migration is woefully deficient." Toth's research is one example that will certainly lead to additional emphasis on hydrogeological approaches to petroleum exploration.

The use of computers and the application of computer models to ground-water systems has increased greatly during the past 10 years. Many of these models were restricted in their use because of the limitations in speed and memory of the available computers. This restriction will not be as severe in the future, and the linkage of flow, transport, and reaction models will become more common. Hydrogeologists dealing with modeling of ground-water systems have felt that the complexity of the models has progressed beyond the capacity of current field techniques to gather reliable data. Konikow and Papadopulos (1988) stated, "In these times of computer models and simulation, it should be reemphasized that the real world is complex, three dimensional, heterogeneous, and commonly anisotropic. This reality can only be described accurately through careful hydrogeologic research in the field." New field techniques must be developed that provide spatially distributed data rather than point data for hydrogeological analysis. Economically efficient remote-sensing techniques will be an area of great impact over the next 10 years.

Our efforts to predict the future of hydrogeology require extrapolating trends, taking educated guesses, and doing some pure speculation. A review of research trends over the past 30 years reveals two paths, one of basic research in flow and ground-water chemistry and a second of applied environmental research. These paths are not parallel; instead, they join, branch, and rejoin repeatedly. Applied research has grown out of the need to develop a better understanding of basic principles of flow and solute transport.

As we enter the 1990s, applied research will focus first on waste disposal, manufacturing, and mining. Future work in this decade will continue to focus not only on characterizing the behavior of hundreds of organic compounds in different flow regimes but also on the testing of methods to treat affected ground-water. Basic research will continue to improve our ability to describe mathematically the behavior of ground water and contaminants in both small- and large-scale problems. This research will require the development of methods to describe more accurately and precisely the spatial variation of aquifer properties. Our modeling capabilities currently outstrip our ability to describe the actual ground-water system; thus, many of the predictions of future impacts are suspect. Some of this ground-water characterization will be led by hydrochemists developing techniques to fingerprint ground water and to date water using scales of weeks instead of hundreds to thousands of years. Our efforts to predict the consequences of past, current, or probable future impacts to a ground-water system will become statistically based, and uncertainty in our work will be better quantified.

Our applied research will begin to expand from hazardous-waste sites to further examination of the consequences of cumulative impacts from dispersed or nonpoint sources (e.g., agricultural chemicals, multiple small-scale mining efforts, and waste disposal of domestic wastes by septic systems). As we attempt to come to grips with these large-scale effects, we will see the development of field and numerical techniques to evaluate these complex and areally extensive problems. Hydrogeochemical research will include the development of additional tools to examine the chemical interaction of more than one solute or fluid in the ground-water system and its transport. Our understanding of the mechanics of the movement of colloidal substances, viruses, and bacteria in soil and ground-water systems will be expanded by joint basic and applied research. Emphasis will also continue on the management of wastes for extreme time periods (i.e., radioactive wastes) and in identifying the pathways and mechanisms for the transport of such wastes. Research efforts will continue to focus on flow and solute transport in fractured systems.

Hydrogeologists are also involved in internationally emerging concerns about global climatic change. Paleohydrogeology and evaluations of potential impacts on hydrologic systems from climatic changes are being investigated.

EDUCATION REQUIREMENTS AND RELATED ISSUES

The average working degree for a hydrogeologist is normally considered to be the Master of Science. Students entering graduate studies should be well versed in geology, engineering geology, or geological engineering, emphasizing the processes that create the geologic framework through which fluid moves (e.g., depositional environments and structural character). Without such a basis, links between complex theory and application are poorly grounded. The hydrogeologist's education also includes a strong background in mathematics, physics, chemistry, and computer programming and application. In particular, knowledge of mathematics, computer science, and quantitative techniques are as necessary as a strong geological background. Without this background, graduates are at a decisive disadvantage.

A traditional geological curriculum is not sufficient today. Students should be required to complete courses in environmental aspects of the earth sciences and related areas, including institutionally oriented courses. Some schools (such as the University of Waterloo) are establishing hydrogeology–environmental science undergraduate majors, which provide the appropriate mixture of traditional geology, mathematics, and other sciences.

To produce qualified hydrogeologists, the curriculum should include courses that describe the geologic framework, such as stratigraphy, structural geology, sedimentation, Quaternary geology, and mineralogy-petrology. Additional desired courses are basic and advanced hydrogeology (which includes components of flow through porous media), surface-water hydrology, aqueous geochemistry or hydrogeochemistry, numerical methods, and field techniques. With this foundation and depending on their interest and degree level, students can then choose additional course work in ground-water modeling, characterization and modeling of vadose zones, ground-water resource analyses, and contaminant hydrogeology and/or contaminant transport modeling. Typically, solutions to hydrogeological problems require an interdisciplinary approach; thus, the student needs to acquire a working knowledge of related fields by taking courses outside the geology department. This course list is not intended to be complete, and rarely are all these courses offered in one department or school.

Although hydrogeology graduates are in demand, a relatively small number of students are graduating each year with M.S. or Ph.D. degrees with this described level of hydrogeological education. The result is a large imbalance between supply (low) and demand (high) for qualified hydrogeologists. Claudy (1991b) pointed out that nongeoscience persons are being hired into geoscience fields because of the decline in the geoscience employment pool. But that only characterizes part of the problem relative to a low supply of hydrogeologists.

The key issue is that productivity from hydrogeology centers of excellence (a critical mass of hydrogeologically oriented faculty on a single campus) does not meet employment demands. Quite the opposite: even allowing for decreasing enrollments, there have been inadequate increases in those geoscience programs predicted to be needed by society and industry for many years to come. The academic problems that affect hydrogeology are retention of students beyond the Bachelor or Master of Science level and underfunding of hydrogeology programs (in terms of equipment, teaching assistantships, and field studies) compared to that awarded to traditional areas of geology, which have fewer students. The interdisciplinary nature of the subject dictates a combination of courses, within and outside the geology department (Stephenson et al., 1981). It is the success of the hydrogeologist's education and subsequent training by the employer that has allowed the discipline to grow to its current level. Those in the discipline are concerned about the next generation.

A FINAL LOOK

The future of hydrogeology will be one of continuing change and development, but throughout it will be led by broadly based individuals with a thorough background in geology. The strength of the discipline is in this understanding of the connection between earth processes and fluid systems.

Hydrogeologists have not been highly successful in communicating about their work either to the public or to the geosciences community. This public-relations task deserves attention.

We close with three thoughts:

- "[Ground water's] importance does not need argument though it may need emphasis" (Chamberlin, 1885).
- "Hydrogeology is a science that has great practical value ..." (Konikow and Papadopulos, 1988).
- "Why justify hydrogeologists at all? They are!" (J. Benoist, 1991, personal commun.)

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REFERENCES CITED

Alvarez, W., 1991, The gentle art of scientific trespassing: GSA Today, v. 1, p. 29–34.

Anderson, M.P., 1979, Using models to simulate the movement of contaminants through groundwater flow systems: CRC Critical Reviews in Environmental Control, v. 9, p. 97–156.

Back, W., 1981, Hydromythology and ethnohydrology in the new world: Water Resources Research, v. 17, p. 257–287.

Back, W., and Freeze, R.A., editors, 1983, Chemical hydrogeology: Stroudsburg, Pennsylvania, Hutchinson Ross, Benchmark Papers in Geology, v. 3, 416 p.

Back, W., Rosenshein, J.S., and Seaber, P.R., editors, 1988, Hydrogeology: The Geology of North America, Boulder, Colorado, Geological Society of America, v. O-2, 524 p.

Bates, R.L., and Jackson, J.A., editors, 1987, Glossary of geology (third edition): Alexandria, Virginia, American Geological Institute, 788 p.

Bredehoeft, J.D., 1976, Status of quantitative groundwater hydrology, *in* Saleem, Z.A., ed., Advances in groundwater hydrology: Minneapolis, American Water Resources Association, p. 8–14.

Bredehoeft, J.D., Back, W., and Hanshaw, B.B., 1982, Regional ground-water flow concepts in the United States; Historical prespectives, *in* Narasimhan, T.N., ed., Recent trends in hydrogeology: Geological Society of America Special Paper 189, p. 297–316.

Chamberlin, T.C., 1885, The requisite and qualifying conditions of artesian wells: U.S. Geological Survey Annual Report 5, p. 125–173.

Claudy, N., 1991a, Geoscience careers—The diversity is unparalleled: Geotimes, v. 36, no. 1, p. 15–16.

Claudy, N., 1991b, Geoscience employment: Geotimes, v. 36, no. 2, p. 57–58.

Domenico, P.A., and Schwartz, F.W., 1990, Physical and chemical hydrogeology: New York, John Wiley & Sons, 824 p.

Fetter, C.W., 1988, Applied hydrogeology (second edition): Columbus, Ohio, Merrill, 592 p.

Freeze, R.A., 1967, Theoretical analysis of regional ground-water flow. II, Effect of water table configuration and subsurface permeability variations: Water Resources Research, v. 3, p. 623–634.

Freeze, R.A., and Back, W., editors, 1983, Physical Hydrogeology: Stroudsburg, Pennsylvania, Hutchinson Ross, Benchmark Papers in Geology, v. 72, 448 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, 604 p.

Freeze, R.A., and Witherspoon, P.A., 1966, Theoretical analysis of regional ground-water flow. I, Analytical and numerical solutions to the mathematical model: Water Resources Research, v. 2, p. 641–656.

Hubbert, M.K., 1940, The theory of groundwater motion: Journal of Geology, v. 48, p. 785–944.

Konikow, L.F., and Papadopulos, S.S., 1988, Scientific problems, *in* Back, W., et al., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The Geology of North America, v. O-2, p. 503–508.

Krabbenhoft, D.P., Bowser, C.J., Anderson, M.P., and Valley, J.W., 1990a, Estimating groundwater exchange with lakes—1. The stable isotope mass balance method: Water Resources Research, v. 26, p. 2445–2453.

Hydrogeology *continued on p. 100*

Bruce F. Molnia

Washington Report provides GSA membership with a monthly window on the activities of the federal agencies, Congress and the legislative process, and international interactions that could impact the geoscience community. In future issues, Washington Report will present summaries of agency and interagency programs, track legislation, and present insights into Washington, D.C., geopolitics as they pertain to the geosciences.

The National Energy Stategy: Powerful Ideas for America?

On March 4, Secretary of Energy James D. Watkins announced that a comprehensive bill, the National Energy Strategy Act, was transmitted to Congress. Arrangements had been made for bipartisan sponsorship of the bill in both the House and Senate. The bill closely parallels the National Energy Strategy (NES) document (subtitled Powerful Ideas for America), released in February. Watkins described the legislative package as relying "on America's strengths: the ingenuity of our people: our leadership in science and technology; and our reliance on free markets and competition to stimulate economic growth and social progress." Watkins also stated, "The actions included in this bill, along with the many non-legislative NES actions, are part of a balanced and comprehensive strategy that could reduce domestic oil consumption by 3.4 million barrels per day (mbd) and increase projected domestic oil production by about 3.8 mbd by the year 2010. Together, the NES initiatives would vastly reduce our economic vulnerability to disruptions in the world oil market." Critics of the NES call it a "non-strategy" and a "non-policy," and focus on the absence of strong conservation and alternative energy measures and on the lack of mandated increases in automobile fuel efficiency, the Federal Corporate Average Fuel Economy rules.

Totaling more than 250 pages, the NES describes itself as laying "the foundation for a more efficient, less vulnerable, and environmentally sustainable energy future." Specific actions not included in the NES because they would result "in higher prices to American consumers, lost jobs, and less competitive U.S. industries" include: "oil import fees; large taxes on gasoline; subsidies for the production of liquid fuels from coal, shale, and natural gas; broadly mandated use of alternative transportation fuels; and sharply higher fuel-efficiency standards that would compel the use of smaller, possibly less safe cars." The NES is not a strong enforcement-oriented directive. The document states that "investment in R&D to increase technology performance and reduce costs is a more appropriate role for the Federal Government than is using taxes or regulations to subsidize or mandate the use of particular technologies."

The purpose of the NES is "achieving greater energy security." This is to be accomplished in four primary thrusts: increasing energy and economic efficiency, securing future energy supplies, enhancing environmental quality, and fortifying foundations. To achieve the first, the NES makes a commitment to "significantly expand its support for R&D on a wide range of more energy-efficient building technologies." To achieve the last thrust, the NES desires to "expand the role of energy science and technology in achieving energy, economic, and environmental objectives" and "promote excellence and productivity throughout the U.S. research establishment," while maintaining "U.S. preeminence in fundamental science and engineering research." This Washington Report focuses on the middle two thrusts.

Securing Future Energy Supplies

Oil. The NES states that "for the foreseeable future, oil will remain a critical fuel for the U.S. and all other industrialized nations." Consequently, the NES proposes initiatives to: reduce the economic consequences of disruptions in world oil markets, and increase domestic oil and petroleum product supplies. Among the measures identified to reduce the impact of oil market disruptions, the NES proposes removal of barriers to investment in petroleum development in countries outside the Persian Gulf and to expanding the Strategic Petroleum Reserve, stored in underground salt caverns at five sites in Texas and Louisiana, to 1 billion barrels. At the start of 1991, the reserve stood at 585.7 million barrels. To increase domestic production, the NES proposes to open access to currently unavailable resources on Federal lands. This includes "environmentally responsible development" in part of the coastal plain of the Arctic National Wildlife Refuge (ANWR) and removing a moratorium now prohibiting leasing of several Outer Continental Shelf (OCS) areas. In June 1990, President Bush deferred leasing of OCS areas including the coasts of Washington, Oregon, and north, central, and southern California, as well as the North Atlantic area, and part of the Gulf of Mexico. A congressional leasing moratorium denies access to all areas under presidential restriction and to other OCS areas in the north Aleutian Basin, the mid-Atlantic, and parts of the eastern Gulf of Mexico. The NES "recommends that the OCS areas currently under congressional moratoria, along with those now available for leasing, be considered . . . in formulating the new 5-Year OCS Program for 1992–1997." Additionally, the NES calls for the accelerated development of "five major discovered fields" on the North Slope of Alaska. The fields are West Sak, Point Thompson, Seal Island/North Star, Gwydyr Bay, and Sandpiper Island. None of these fields is undergoing development now. The NES will also deregulate oil pipelines, implement oil and gas tax incentives, increase the production and export of California heavy oil, and promote horizontal well drilling. Last, the NES recommends that the Administration request that Congress authorize leasing of the Elk Hills Naval Petroleum Reserve in California.

Natural Gas. The NES states that the natural gas industry "continues to be hampered by inefficient and outmoded regulation." Consequently, the NES will try to remedy this problem by: expediting gas pipeline construction, streamlining the National Environmental Policy Act process associated with natural gas pipeline construction, deregulating sales rates, reforming the design of natural gas pipeline pricing structure, improving access to natural gas pipeline transportation services, eliminating the Department of Energy's oversight of import and export transactions, and encouraging the use of natural gas as an alternative transportation fuel.

Coal. Coal is the most abundant fossil fuel in the United States. To take advantage of "our enormous, low-cost coal reserves," the NES defines two goals for coal's future: maintain coal's competitiveness while meeting environmental, health, and safety requirements; and creating a favorable export climate for U.S. coal and coal technology. To accomplish these goals, the NES identifies the need to develop and demonstrate new clean coal technologies, reduce uncertainty over environmental regulation, provide regulatory incentives in commercial deployment of new clean coal technology, and remove barriers to construction of coal slurry pipelines.

Nuclear Power. The NES states that if utility executives once again consider the "nuclear option" technically, politically, and economically feasible when new power capacity is needed, then power generation from nuclear plants could double by 2020. The NES will reform the nuclear power licensing process, provide a site and strategy for proper management and disposal of high-level nuclear wastes, and encourage the development of light-water reactors incorporating the concept of "passive safety." The NES goal is to have a demonstration plant for production of inertial or magnetic fusion energy operating by about 2025 and a commercial powerplant by 2040.

Enhancing Environmental Quality

Critics have attacked the NES for being especially weak in its concern about the environment. The NES, however, presents a different opinion. According to the NES document, the NES proposes action that will improve public health; enhance the quality of our air, water, and land; and protect the global environment. This will be accomplished by: use of market mechanisms; increased efficiency in every phase of energy production, transformation, and use; increased use of natural gas; development of cost-competitive renewable energy supplies; development and use of cleaner transportation fuels, including reformulated gasoline; development and use of clean coal technologies; improvements in the process used to site energy facilities, including refineries; and reduction in the production of energy-related and other industrial wastes. ■

Future Washington Reports will keep you posted on the progress of the National Energy Strategy Act through the Congress, and on the fate and implementation of the National Energy Strategy.

Hydrogeology *continued from p. 99*

Krabbenhoft, D.P., Anderson, M.P., and Bowser, C.J., 1990b, Estimating groundwater exchange with lakes—2. Calibration of a three-dimensional, solute transport model to a stable isotope plume: Water Resources Research, v. 26, p. 2455–2462.

Maxey, G.B., 1979, The Meinzer era of U.S. hydrogeology, 1910–1940, *in* Back, W., and Stephenson, D.A., eds., Contemporary hydrogeology (Journal of Hydrology, George Burke Maxey memorial volume): Amsterdam, Elsevier, p. 1–6.

Meinzer, O.E., 1923a, Occurrence of ground water in the United States with a discussion of the principals: U.S. Geological Survey Water-Supply Paper 489, 321 p.

Meinzer, O.E., 1923b, Outline of ground-water hydrology, with definitions: U.S. Geological Survey Water-Supply Paper 491, 71 p.

Meyer, G., Davis, G., and Lamoreaux, P.E., 1988, Historical perspective, *in* Back, W., et al., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The Geology of North America, v. O-2, p. 1–8.

Moore, J.E., and Rosenshein, J.S., 1990, Hydrogeology: Geotimes, v. 35, no. 2, p. 27–28.

Narasimhan, T.N., editor, 1982, Recent trends in hydrogeology: Geological Society of America Special Paper 189, 448 p.

Rosenshein, J.S., Moore, J.E., and Wood, W.W., 1991, Hydrogeology: Geotimes, v. 36, no. 2, p. 51–52.

Schwartz, F.W., et al., 1990, Ground water models—Scientific and regulatory applications (Committee on Ground-Water Modeling Assessment, Water Science and Technology Board): Washington, D.C., National Academy Press, 303 p.

Stephenson, D.A., 1978, So how come our well has gone dry?: Wisconsin Academy Review, v. 24, no. 4, p. 17–20.

Stephenson, D.A., et al., 1981, Coal mining and ground-water resources in the United States (Committee on Ground-water Resources, Board on Mineral and Energy Resources, National Research Council): Washington, D.C., National Academy Press, 197 p.

Toth, J., 1962, A theory of groundwater motion in small drainage basins in central Alberta: Journal of Geophysical Research, v. 67, p. 4375–4387.

Toth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal of Geophysical Research, v. 68. p. 4795–4812.

Toth, J., 1988, Ground water and hydrocarbon migration, *in* Back, W., et al., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The Geology of North America, v. O-2, p. 485–502.

Travis, C.C., and Doty, C.B., 1990, Can contaminated aquifers at Superfund sites be remediated?: Environmental Science and Technology, v. 24, p. 1464–1466. ■

Nominations Open for AAAS/ Westinghouse Award

The American Association for the Advancement of Science invites nominations for the 1990 AAAS/Westinghouse Award for Public Understanding of Science and Technology. This annual award recognizes scientists and engineers who make outstanding contributions to the popularization of science and are *not* members of the media. It will be presented at the AAAS Annual Meeting in Chicago, Illinois, February 6–11, 1992. The award carries a $2500 stipend.

Types of contributions to be considered include: publishing, broadcasting, lecturing, museum presentation and exhibit design, and other public outreach activities.

The deadline for nominations is August 1, 1991. For further information, contact Patricia S. Curlin, AAAS, 1333 H St., N.W., Washington, DC 20005; (202) 326-6602.